Unfinished Upgrades to CANDU Reactors that can Reduce Risk From Severe Accidents

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The most painful lessons that we may learn from reviews of the Fukushima disaster relate to the failure of regulators, designers and utilities in better retrofitting existing, operating reactors in a timely manner to withstand and mitigate known severe accident related challenges to reactor core and containment integrity.

- PHWR reactors present very special severe accident mitigation capabilities as well as challenges due to their specific design features.
- Operating PHWRs are ‘safe’ in that they meet their design basis to a very large extent.
- These reactors were just not designed with severe core damage accidents within the design basis.
- A number of PHWR inherent design features may lend favourably to mitigation of some portions of severe accidents but they have no natural, inbuilt ability to universally extend their design advantages to severe accidents.
• **Severe Core Damage Frequency**
  – Limit: 1E-04 events/year; Goal: 1E-05 events/year

• **Large Release Frequency**
  – Limit: 1E-05 events/year; Goal: 1E-06 events/year
  – Maximum off site release must be less than
    100 TBq of Cs-137 (LR); 1000 TBq of I-131 (SER).
    (There are ~70,000 TBq in a CANDU 6 at equilibrium. Cs-137 is about 3.2 TBq/g. Release of about 31g of Cs-137 will exceed the limit.)

• **No Containment Failure or Bypass**
  – The maximum containment pressure remains lower than the containment failure pressure for up to 24 hours after the onset of a severe accident.
  – The maximum pressure/temperature/radiation field at containment seals, penetrations and doors are below the failure limits for the seals and the containment, whichever is lower.
  – The hydrogen concentration remains below the limits for deflagration in any given volume of the containment.

• **Long Term Cold Shutdown and Control**
  – Known and controllable reactor state;
  – The debris have adequate area to spread in the reactor vault and there is high confidence that any debris in the reactor vault are covered with water
  – No recriticality
HTS Response to onset of station blackout

HTS over pressurizes due to undersized valves

Cannot manually depressurize HTS

Cannot inject into HTS at high pressures
STATION BLACKOUT PROGRESSION

Cannot manually remove non condensable gases

Poor deuterium / hydrogen detection and mitigation

Potential traps of hydrogen

Un-attenuated expulsion of fission products into containment

Inadequate pressure relief

Low pressure penetration failures

Cannot vent containment in emergency

Early pressure boundary ruptures

Forces moderator expulsion

Steam explosion potential

Vessel potentially cannot hold debris

Concrete Vault cannot tolerate energetic interactions

Cannot vent containment in emergency
CANDU 6 REACTOR SEVERE ACCIDENT ISSUES

Containment bypass potential

Large amount of steel & Zircaloy for oxidation

External hookups for water and power do not exist

CANDU severe accident challenges and opportunities for coordinated action to reduce risk.
CANDU severe accident challenges and opportunities for coordinated action to reduce risk.

- Much of CANDU severe accident progression phenomena poorly understood
- No severe accident simulators
- Inadequate and ‘black box’ severe accident computer codes
- Inadequate off-site radiation measurements for source term correlation
- MCR habitability issues (e.g. main steam line on top of MCR)
- Severe Accident related in-core instrumentation does not exist
- Inadequate Class 1 batteries
- Emergency external hookup power distribution and coolant injection systems do not exist
- Irradiated fuel bay not qualified for prolonged loss of power
CANDU severe accident challenges and opportunities for coordinated action to reduce risk.

<table>
<thead>
<tr>
<th>Lmin [m]</th>
<th>Lmax [m]</th>
<th>Lavg [m]</th>
<th>CHANNEL POWER MAP</th>
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<tr>
<td>A</td>
<td>6.2</td>
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<tr>
<td>B</td>
<td>7.3</td>
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<tr>
<td>C</td>
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<tr>
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<td>H</td>
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<td>O</td>
<td>10.9</td>
<td>14.4</td>
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<tr>
<td>P</td>
<td>11.6</td>
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<tr>
<td>Q</td>
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<tr>
<td>W</td>
<td>16.7</td>
<td>17.8</td>
<td>17.3</td>
</tr>
</tbody>
</table>
CANDU severe accident challenges and opportunities for coordinated action to reduce risk.
Minimum moderator expulsion upon boiling
= 5% + carryover

Estimated moderator expulsion upon in-core rupture = 20%
CANDU severe accident challenges and opportunities for coordinated action to reduce risk.

FUEL HEATUP HIGH ENOUGH?

CATHENA Runs, AECL Fuel Branch 2000
CsI, CsOH fuel release rates

CORSOR-M
NUREG-0772
FP release a strong function of temperature

<table>
<thead>
<tr>
<th>gap release</th>
<th>release of volatiles</th>
<th>release of semi-volatiles</th>
<th>release of refractory metals / ceramics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe, Kr, I, Cs</td>
<td>Te</td>
<td>Sr, Ba</td>
<td>Ru, La, Ce</td>
</tr>
</tbody>
</table>

- Zr oxidation: steel melting, Eutectic dissolution, fuel (UO₂) melting
- clad failure: core heatup, degradation, and relocation, core-concrete interactions

<table>
<thead>
<tr>
<th>Temperature (C)</th>
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<tbody>
<tr>
<td>1000</td>
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</table>

CANDU severe accident challenges and opportunities for coordinated action to reduce risk.
H$_2$ PRODUCTION RATES BY ZR-STEAM REACTION

Maximum H$_2$ produced by oxidation of fuel bundle, PT and CT zircaloy

Maximum H$_2$ produced by oxidation of fuel bundle and PT zircaloy

Maximum H$_2$ produced by oxidation of fuel bundle zircaloy

T=1200K

T=1500K

T=1800K

T=2100K

Time [s]

Hydrogen [kilo mole]
Steel Oxidation

Fig. 1. Parabolic rate constants for iron oxidation in air or oxygen in the range of 700–1250°C.

Review of the High-Temperature Oxidation of Iron and Carbon Steels in Air or Oxygen

R. Y. Chen* and W. Y. D. Yan†
Enough hydrogen to burn or detonate?

- Volumetric dilution of hydrogen
- 43,286 kg Zirconium
- 48,000 m³ Containment
- 948 moles of H₂ for 100% oxidation

Graph: VOLUME % H₂ IN CONTAINMENT vs. % METAL-WATER REACTION
- No steam
  - P = 100 to 150 kPa
- AIR + STEAM + H₂
  - P = 450 kPa
Likely Severe Accident Outcomes

- Like in all power reactors, a severe core damage accident will release enough energy to fail containment unless the released energy is removed sufficiently.

- Enough Fission Products will be released quickly from fuel and debris and appear directly in the containment.

- Containment integrity and avoidance of containment bypass become important issues.

- Acceptance criteria will not be met under most probable severe core damage scenarios with little positive operator intervention.

- Need to close the uncertainties in rates, not just magnitudes and timing of major events.
SEVERE ACCIDENT MITIGATION ISSUES

- Cernavoda reactors did not consider severe accidents in the design process.
- Current CANDU6 design inherently forces a reactor damage even before an ECC loss leading to severe core damage.
- No provisions for depressurization after SBO.
- No provision for emergency injection into HTS at high pressures.
- Onset of a severe core damage in a CANDU reactor puts activity directly into the containment. There is no holding of activity in a vessel like in a PWR.
- Significantly higher sources of hydrogen from large amounts of steel and Zircaloy.
- Enhanced potential for steam explosions due to melt relocations pathways.
- Pressure relief in ALL relevant reactor systems in inadequate (PHTS, Calandria, Shield Tank, Containment)
SEVERE ACCIDENT MITIGATION ISSUES

- Calandria vessel cannot contain debris and can fail catastrophically.
- Reactor vault cannot contain pressure upon boiling and can fail.
- Inadequate instrumentation and control.
- Poor equipment survivability
- Current PARS inadequate and potentially dangerous.
- No dedicated operator training / simulators for severe accidents.
- Severe accident simulation methods are outdated, crude and inadequate.
- No significant design changes implemented. Known problems ignored.
- Current SAMGs are inadequate. Emergency hookups not implemented
- High risk potential from external events
- Need to reconsider malevolent actions and sabotage.
CANDU 6 design Improvements to reduce risk

1. Internal and External hookups for adding supplementary feedwater to boilers

   - Passive makeup of boiler inventory by a pump with an alternate source of local power, e.g. steam driven auxiliary feedwater pump;

   - De-aerator location and control enhancements for provision of gravity fed deaerator water inventory to boilers

   - External hookup for water injection into boilers (e.g. by fire trucks or demineralised water system or other sources) in conjunction with instrumentation to measure actual water level, pressure and temperature in the boilers.

   - External Hookups to provide external power to feedwater pumps or auxiliary feedwater pumps.
2. PHTS manual depressurization
   - passive system for depressurization without inventory loss
   - manual depressurization with manual relief valves

3. Means to remove non condensable gases from the PHTS and enhancement measures for thermosyphoning

4. High pressure emergency PHTS water makeup from internal and supplemental external sources

5. PHTS overpressure protection system enhancements
   - DCRV size increase

6. Design Reviews for avoidance of containment bypass
7. Additional hookups and monitoring of support services (RCW, RSW)

8. Calandria vessel overpressure protection enhancements for avoidance of deliberate voiding of moderator
   - additional pressure relief at pressure lower than rupture disk actuation pressure
   - pressure relief at 2 MPa

9. Internal and external systems for supplementary heat removal by moderator cooling system

10. Internal and external systems for supplementary makeup and recovery of moderator water inventory

11. Calandria vessel structural design enhancements for retention of core debris
    calandria vessel not an assured core catcher
12. Reactor vault heat removal capacity enhancements for retention of debris in Calandria vessel

13. Calandria vault overpressure protection enhancements for avoidance of structural failure

14. Water addition to Shield tank and increased reliability of end shield cooling system

15. Containment improvements to promote natural circulation of air from locations where combustible gases may be trapped.

16. Containment pressure suppression improvements: intelligent dousing, local sprays and external support to coolers
17. Containment reinforcements for avoidance of early overpressure failures

18. Deuterium / Hydrogen removal systems
   - hydrogen source term consistent with international norms + other CANDU specific sources such as incore devices and steel in feeders
   - recombiner type, number and impact on containment

19. Deuterium / Hydrogen detection and measurement systems

20. Emergency Filtered Containment Venting for containment depressurization

21. Measures for prevention and mitigation of consequential failures, floods, fires
22. Post Accident Monitoring - Instrumentation and controls upgrades for survival and functionality to monitor reactor state and maintain control

23. Upgrading of components, systems and instrumentation necessary for severe accident management for survivability

24. Upgrading of control room & secondary control room for habitability

25. Measures for reduction of off-site releases and doses

26. Off-site measurements of releases and correlating them to source terms and development of dose prediction tools at unmonitored locations
27. Development and implementation of an Emergency (severe accident) electrical power distribution system

28. Improved Class 1 batteries. Better definition of anticipated loads over prolonged periods of loss of AC power.

29. Fuelling machine considerations

30. Irradiated fuel bay considerations

31. Development of computational aids including better integrated codes for prediction of severe accident progression

   Need more detailed code with better representation of the reactor
32. Evaluation of effect of severe accidents in all units of a multi-unit station.

33. Development of station specific SAMG with consideration of design upgrades

34. Simulator development and operator training in severe accident management
   Advanced computational aides and simulator training

35. Implementation of an Emergency Technical Support Center

36. Enhancements to the Secondary Control Area

37. Measures for emergency preparedness and transfer of instructions and information to public

38. Sabotage, malevolent acts and other security considerations
Uncontrolled pressurization potentially occurs in CANDU HTS prior to severe core damage and in other systems after severe core damage.

**Primary Heat Transport System**
- PRIOR TO FUEL DAMAGE
- AFTER FUEL DAMAGE

**Calandria Vessel**
- PRIOR TO SEVERE CORE DAMAGE

**Shield Tank – Reactor Vessel**
- AFTER SEVERE CORE DAMAGE

**Containment**
- BEFORE FUEL DAMAGE
- AFTER SEVERE CORE DAMAGE
CANDU severe accident challenges and opportunities for coordinated action to reduce risk.
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### Examples of CANDU SRV relief capacity

<table>
<thead>
<tr>
<th></th>
<th>Pressure</th>
<th>Liquid</th>
<th>Steam</th>
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<tbody>
<tr>
<td></td>
<td>m³/s</td>
<td>MPa</td>
<td>kg/s</td>
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<tr>
<td><strong>PICKERING</strong></td>
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<tr>
<td>4 LRVs</td>
<td>0.256</td>
<td>9.55</td>
<td>197.3</td>
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<tr>
<td>2 SRV</td>
<td>0.060</td>
<td>8.1 to 8.6</td>
<td>47.0</td>
</tr>
<tr>
<td><strong>CANDU 6</strong></td>
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<td></td>
<td></td>
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<tr>
<td>4 LRVs</td>
<td>0.133</td>
<td>10.24</td>
<td>100.8</td>
</tr>
<tr>
<td>2 SRV</td>
<td>0.062</td>
<td>10.056</td>
<td>53.4</td>
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</table>
Theoretically max choked Steam Flow through a hole for a range of pressures (kPa)

<table>
<thead>
<tr>
<th>Station</th>
<th>Design Steam discharge rate at ~10 MPa</th>
<th>Industry Claims of Extrapolated Steam Discharge Capacity at 12 Mpa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gentilly-2</td>
<td>~2 kg/s</td>
<td>&gt;16 kg/s</td>
</tr>
<tr>
<td>Pt. Lepreau</td>
<td>~2 kg/s</td>
<td>&gt;13 kg/s</td>
</tr>
<tr>
<td>Bruce A &amp; B</td>
<td>~1.5 kg/s</td>
<td>&gt;13 kg/s</td>
</tr>
<tr>
<td>Darlington</td>
<td>~1.5 kg/s</td>
<td>&gt;30 kg/s</td>
</tr>
<tr>
<td>Pickering A &amp; B</td>
<td>~1.5 kg/s</td>
<td>&gt;30 kg/s</td>
</tr>
</tbody>
</table>

Maximum possible steam discharge capacities

CANDU severe accident challenges and opportunities for coordinated action to reduce risk.
EXAMPLE OF UNDESIRABLE RESPONSE

ROH Pressure during Sustained Loss of Heat sinks - Slow DGC RV Opening

- **PHTS pressurizes; DGC RV discharge becomes all liquid when DGC level rises above the relief line connection.**
- **LRVs open.**
- **SGs nearly empty.**
- **DGC full.**
- **DGC RV discharge becomes mostly steam.**
- **DGC level falls, steam enters relief line.**
- **PT predicted to fail.**

Source: AECL 2011
Typical unmitigated SBO response

Figure 5-28  Unmitigated STSBO primary and secondary pressures history

Source – NUREG/CR 7110
Another unmitigated SBO overpressurization

Primary and Secondary Pressures
LTSBO - No Mitigation With Portable Equipment

- Pressurizer
- SG A
- SG C
- SG B

Start RCS cooldown
Emerg CST empty
Batteries exhausted
S/G PORVs reclose
Hot leg creep rupture

Figure 5-1 Unmitigated LTSBO primary and secondary pressure history

Source – NUREG/CR 7110
Typical LWR SRVs (Diablo Canyon)

Typical PWR SRV Steam relief capacity = 53 kg/s per valve through **three to five** spring-loaded, enclosed poppet-type, self-actuated angle relief valves with backpressure compensation.
CALANDRIA VESSEL INTEGRITY ISSUES

7.6 m dia, 4 m long inner shell

6.8 m dia, 1m long outer shells

Moderator discharge penetrations

CANDU severe accident challenges and opportunities for coordinated action to reduce risk.
CALANDRIA VESSEL SHELL STRUCTURE

CANDU severe accident challenges and opportunities for coordinated action to reduce risk.
Debris assumed 3m wide

Decay heat transfer [Mw]

Temperature [°C]

Axial Thermal Expansion [mm]

Inner surface temp [°C]
Average temp [°C]
Outer Surface temp [°C]
Thermal expansion [mm]
CANDU severe accident challenges and opportunities for coordinated action to reduce risk.
Transient thermal-hydraulics and physical-chemistry of severe accidents is uncertain and Rate of H₂ production in a multi-component solid debris / melt is not well understood.

\[ \text{Zr} + 2\text{H}_2\text{O} = \text{ZrO}_2 + 2\text{H}_2 + 293.2 \text{ kJ/mole of H}_2 \]

- Reaction heat \( \sim \) 6.44 MJ/kg of Zr.
- 43.2 Mg of Zircaloy in a CANDU 600 core will produce about 1900 kg of H₂ (950 k moles in a 2000 k mole air containment)
- Will need 17.1 Mg of Steam to fully Oxidize
- Will Produce 278 GJ of energy that is about 135 FPS of thermal power (or 3.76 hours of decay power at 1%)

\[ \text{H}_2 + \frac{1}{2}\text{O}_2 = \text{H}_2\text{O} + 240 \text{ kJ/mole of H}_2 \]

- If recombined with Oxygen in a recombiner, only the hydrogen from Zircaloy will produce 225 GJ of energy (equivalent to 110 FPS, 3 hours of decay power at 1%).
EXAMPLE OF A TYPICAL PARS UNIT - AREVA PARS
RECOMBINER EFFECTIVENESS – 100% Zr Oxidation

Sample First order Recombiner Sizing Calculations
Severe Accident Source Term - 100% Zirc Oxidation (960 k mole H2)
Energy Release rate into containment
Severe accident Source Term - 100% Zirc Oxidation
EXAMPLE OF RECOMBINER CAPABILITIES

- washcoat coating
- coating with adapted conversion capacity

![Graph showing H₂ concentration vs. vol % with data points and trend lines at 1.0 m/s.]
THERMAL ISSUES

Graph showing the relationship between H₂ concentration (vol.%) and some unspecified property. The graph includes data points and a trend line, with annotations indicating washcoat coating and coating with adapted conversion capacity. The graph is labeled with a velocity of 1.0 m/s.
SEVERE ACCIDENT TRAINING SIMULATOR DEVELOPMENT
SIMULATIONS TO LEARN & TRAIN FOR A SEVERE ACCIDENT